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Preheating method of lithium-ion batteries in an electric vehicle

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Abstract To improve the low-temperature charge-discharge performance of lithium-ion battery, low- temperature experiments of the charge-discharge characteristics of 35 Ah high-power lithium-ion batteries have been conducted, and the wide-line metal film method for heating batteries is presented. At −40 °C, heating and charge-discharge experiments have been performed on the battery pack. The results indicate the charge-discharge performance is substantially worse in cold climates, and can be significantly improved by heating the battery pack with a wide-line metal film. Pulse charge-discharge experiments show that at −40 °C ambient temperature, the heated battery pack can charge or discharge at high current and offer almost 80% power.

Keywords Lithium-ion battery, Charge-discharge characteristics, Low-temperature performance, Electric vehicles, Heating method

1 Introduction

In recent years, electric vehicles have developed rapidly. In-depth research work in many countries has improved all aspects of electric vehicle technology so that urban pollution can be reduced, and fruitful results have been achieved. Battery energy storage is one of the key components in electric vehicles, so it receives strong research attention and has developed rapidly as a result. The performance and cost of an electric vehicle depends strongly on the performance and service life of its battery. Currently, battery chemistries used in electric vehicles include lead-acid, nickel cadmium, nickel metal hydride, lithiumion, and supercapacitors [1]. Lithium-ion is gradually replacing other chemistries to become the most common battery technology found in electric vehicles due to its advantages of high power, high energy density, long cycle life, low self-discharge rate, long shelf life and low pollution [2, 3].

With their increased use, the low-temperature performance of lithium-ion batteries begins to attract attention. At low temperature, the charge-discharge performance of lithium-ion batteries significantly reduces [4–6]. Generally, the solid electrolyte interface film, surface charge transfer impedance and Li+ diffusion in the electrode are the main influences on low-temperature performance of lithium-ion batteries [7–10]. So far, it is difficult to improve their performance through innovations in the batteries' materials. Therefore, auxiliary methods to improve the low-temperature performance of lithium-ion batteries become an important research direction, i.e., the AC heating method [11–13], preheating method [14–16], heating plate method [17] and heating bag method [18]. This paper studies the charge-discharge performance of a 35Ah@3.7V $LiMn_2O_4$ battery in a 8×8 wheeled electric vehicle from 20 °C to −40 °C. Awide-line metal film is proposed to heat the battery so as to meet the low-temperature operating requirements of the 8×8 wheeled electric vehicle. Experimental results prove that the wide-line metal film heating method can significantly improve the low-temperature performance of the battery.

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2 Test platform for the Li-ion battery

A diagram of the test platform is shown in Fig. 1. Cell-level charge-discharge testing is performed by the HT-V5C200D200 which is manufactured by the LTD company in Guangzhou. Its maximum voltage of charge-discharge is 5 V, and its measurement precision can reach 0.1 mV. Battery-pack testing is performed by the Digatron EVT500-500 which is manufactured by the Digatron Company in Germany. Its maximum current and voltage of charge-discharge are 500 A and 500 V respectively. The function of the thermostatic enclosure is to provide the environment for the tests. The electrochemical workstation produced by the Zahner Company in Germany is used to measure the AC impedance spectra of the battery and the impedance value at a fixed frequency. Its measurement frequency range and AC amplitude are 10 μHz-4 MHz and 1 mV-1 V respectively with frequency accuracy of 0.0025%.The tested battery is a 35Ah@3.7V $LiMn_2O_4$ cell, with cathode of spinel structure $LiMn_2O_4$, anode of artificial graphite, and shell of Al-plastic film. For battery-packtesting, a string of three cells is constructed.

3 AC impedance variations of the battery cell at low temperature

Battery internal resistance is one of the important parameters. To determine the change of battery internal resistance at low temperature, this paper measured the AC impedance of the battery placed in a −40 °C thermostatic enclosure. The DC internal resistance of battery cannot be measured directly because charging and discharging with a DC current will change the state of the battery: its temperature and charge level. Therefore we use the electrochemical workstation to measure the AC impedance of the battery. Figure 2 is an AC impedance spectrum of the Li-ion battery cell at 20 °C, as the frequency is varied from 1 Hz to 100 kHz and the voltage is 5 mV. The magnitude of the AC impedance varies very little at low frequencies (<1 kHz), and its phase is close to zero, thus the AC impedance of battery at low frequencies can be thought as the internal resistance. Because the AC impedance is almost minimum at 260 Hz, this frequency is used to measure the AC impedance of the battery in experiments. Figure 3 is an impedance curve of a Li-ion cell during the eight hours after it was placed in a −40 °C enclosure. It shows that impedance of battery rapidly increased with standing time at first, but impedance of battery is almost constant after 3.5 hours. Therefore, the battery requires 3.5 hours to reach thermal equilibrium with its environment.

4 Influence of low temperature on the discharge performance

To study the effect of low temperature on the discharge performance of the battery, a cell placed in different low-temperature environments was discharged at several different constant currents. Firstly, the cell was charged at 1C/3 at room temperature. Secondly, the cell was placed in the thermostatic enclosure for five hours to reach thermal equilibrium. Finally, the cell was discharged at constant current until its voltage reduced to 3 V, and a discharge

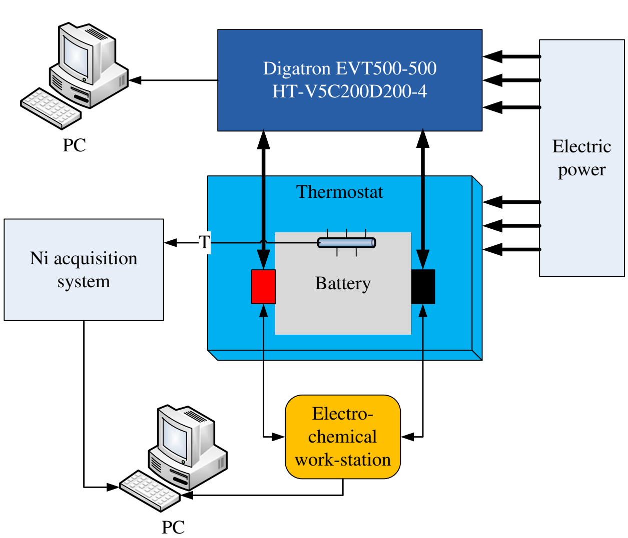

Fig. 1 Diagram of the test platform

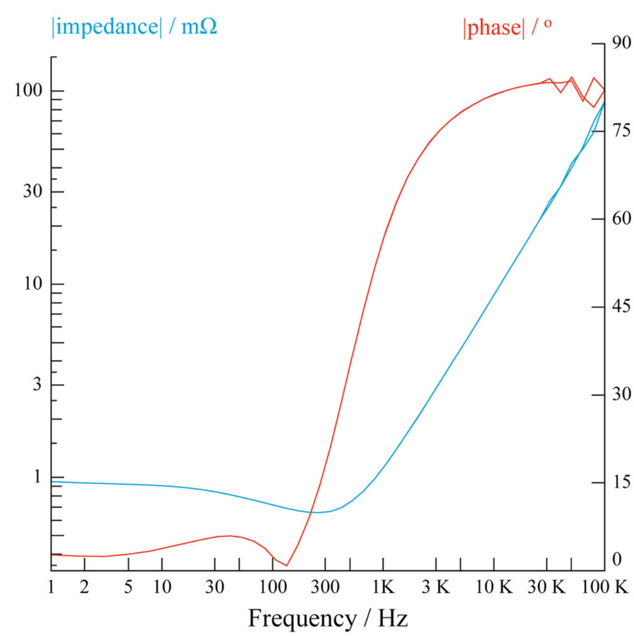

Fig. 2 Impedance spectroscopy of a Li-ion cell at 20 °C

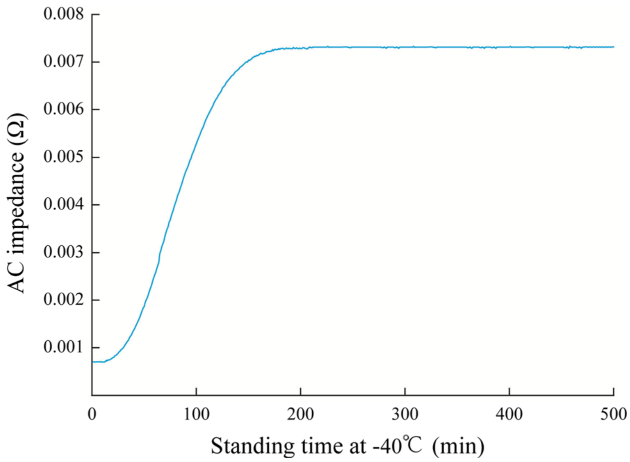

Fig. 3 Impedance convergence of a Li-ion cell at −40 °C

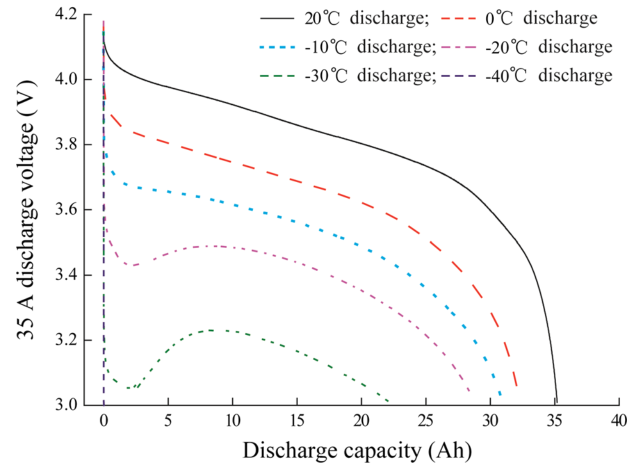

Fig. 5 35 A discharge curves of a Li-ion cell at various temperatures

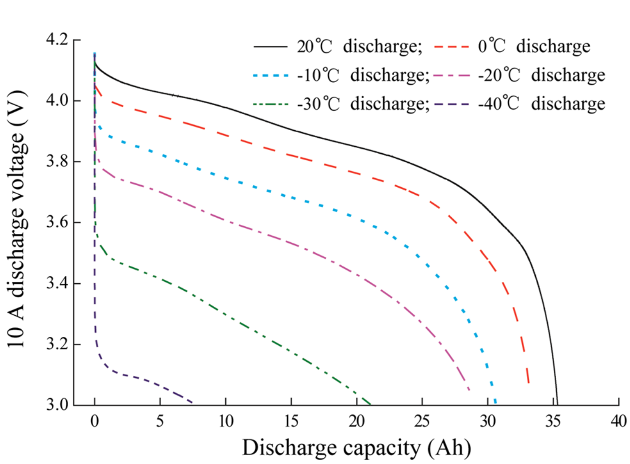

Fig. 4 10 A discharge curves of a Li-ion cell at various temperatures

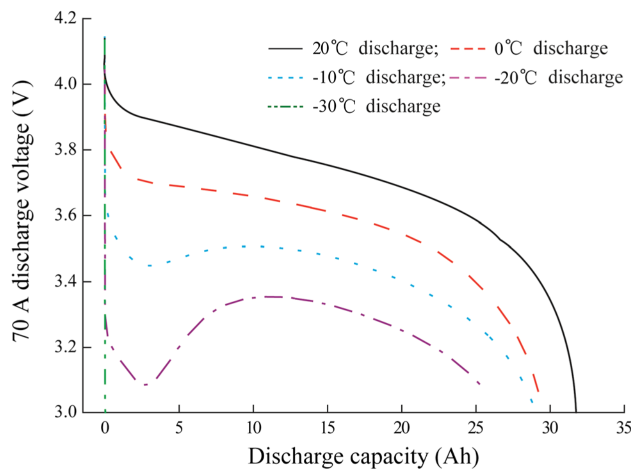

Fig. 6 70 A discharge curves of a Li-ion cell at various temperatures

curve was produced by graphing the voltage and the discharge capacity calculated as current multiplied by elapsed time. The discharge curves of the cell at different low temperatures are shown in Figs. 4, 5 and 6 for 10 A, 35 A, and 70 A discharge currents respectively. The experimental results show that the discharge capacity of the cell declines when its temperature decreases. Moreover, the voltage collapses rapidly at temperatures −10 °C and below, and then recovers for a while before descending below 3 V. In low-temperature environment, the internal resistance of the battery is greatly increased, therefore the voltage of the battery reduces rapidly at the beginning of discharging. Meanwhile, the battery will be heated and the voltage of the battery rise because of the internal resistance during discharging. This collapse-recovery behaviour must give some clue about the physical causes of reduced discharge capacity and should be investigated further.

5 Influence of low temperature on the charge performance

To study the effect of low temperature on the charge performance of the battery, a cell placed in different low-temperature environments was charged at several different constant currents. Firstly, the cell was discharged at 1C/3 at room temperature. Secondly, the cell was placed in the thermostatic enclosure for five hours to reach thermal equilibrium. Finally, the cell was charged at constant current until its voltage reached 4.2 V. The charge curves of the cell at different low temperatures are shown in Figs. 7 and 8 for 10 A and 35 A charge currents respectively. Compared with the low-temperature discharge performance, the charge performance of the cell is even more degraded. Under 0 °C, it can't charge normally even at low current, and at high current the voltage of the cell reaches

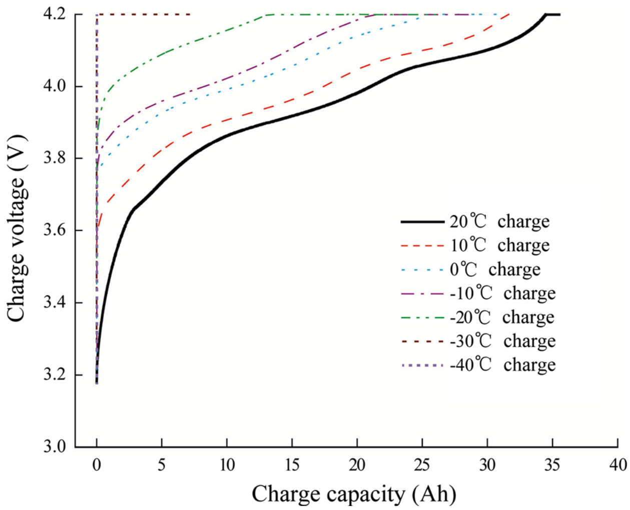

Fig. 7 10 A charge curves of a Li-ion cell at various temperatures

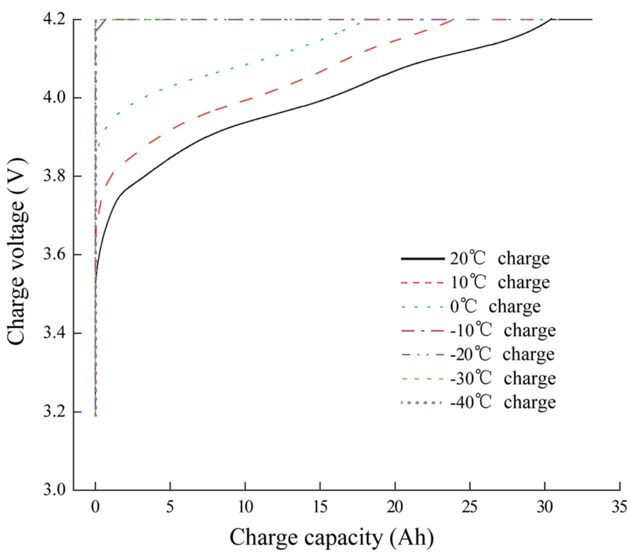

Fig. 8 35 A charge curves of a Li-ion cell at various temperatures

4.2 V immediately. This is why no results are shown for 70 A charging current.

6 Wide-line metal film heating method

The experiments reported above (as shown in Fig. 3) prove that the internal resistance of the battery is greatly increased and the charge-discharge performance is significantly reduced at low temperatures. The performance of an electric vehicle is limited by the low-temperature performance of its batteries, and this is especially for special-purpose electric vehicles that are required to operate under a great variety of temperature conditions. To meet the high reliability requirement of the 8×8 wheeled electric vehicle, a wide-line metal film heating method is proposed, in which two pieces of wide-line metal film are placed on the two largest surfaces of the battery cell. The wide-line metal film is printed on a FR4 board or aluminum PCB, and its thickness is 1 mm. One side of the wide-line metal film is a complete rectangular copper film, and the other side is a certain width of continuous copper wire. The thickness of copper film and copper wire is 0.035 mm. The copper wire is heated by passing anelectric current through it. The heat is distributed evenly to the battery by the copper film on the other side. The structure of the heating device is simple, and it can be installed conveniently in order to heat batteries without changing the structure of the original battery pack.

7 Experiments on the low-temperature heating

To study the recovery of low-temperature charge and discharge performance of a battery pack that is heated by the wide-line metal film, three 35Ah@3.7V $LiMn_2O_4$ battery cells were connected in series to form a battery pack. The wide-line metal film was installed in four heaters between three cells between two battery cells as shown in Fig. 9.

In order to make the heating experiments conform closely to the conditions of a vehicle battery, the battery pack with the wide-line metal film was put into a battery box. Figure 10 shows the battery box placed in the thermostatic enclosure that is set to −40 °C. The standing time of the battery box was increased from 5 hours to 8 hours to reach thermal equilibrium because the battery box assembly has a higher thermal inertia. The wide-line metal film began to heat the battery pack after 8 hours.

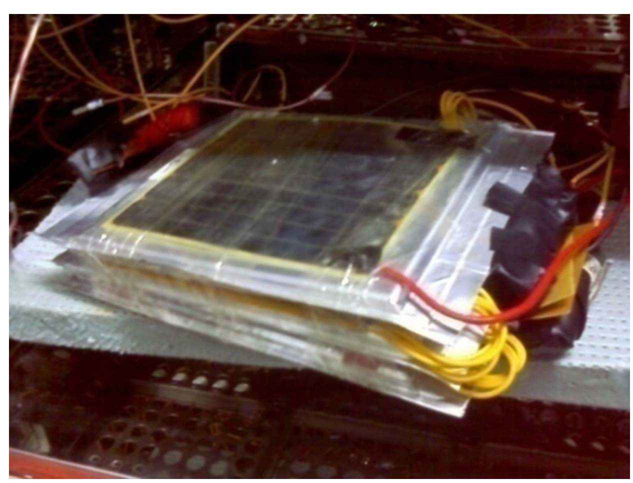

Fig. 9 Photograph of the battery pack and heater

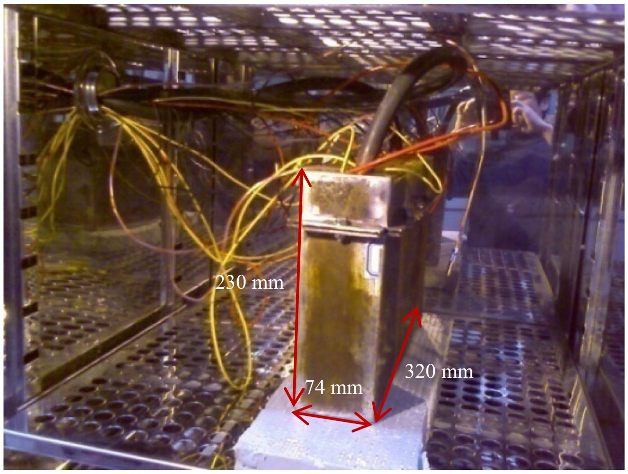

Fig. 10 Photograph of the battery box inside the thermostatic enclosure

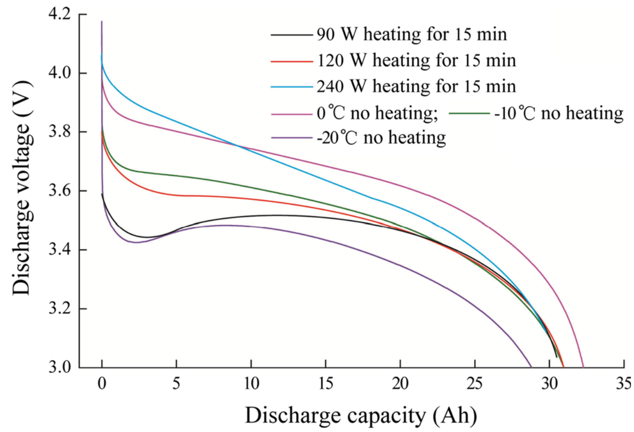

Fig. 12 35 A discharge curves of the unheated cell and heated battery pack

7.1 Discharge performance of battery pack at −40 °C after heating for 15 min

Figure 11 shows three 1C constant current discharge curves of battery pack after it is heated for 15 min by 240 W, 120 W and 90 W power to the wide-line metal film. In all cases, the full discharge capacity of just over 35 Ah is achieved for the series-connected cells, as can be seen by comparing with Fig. 5, while the voltage in the early and middle stages of discharge increases with increasing heating power. The average discharge voltage of the battery is 0.53 V higher when heated by 240 W power compared to 90 W power, and the maximum voltage differential is 1. 38 V. Therefore, increasing the heating power above 90 W can improve the discharge voltage and thereby increase the discharge power but does not significantly affect the discharge capacity.

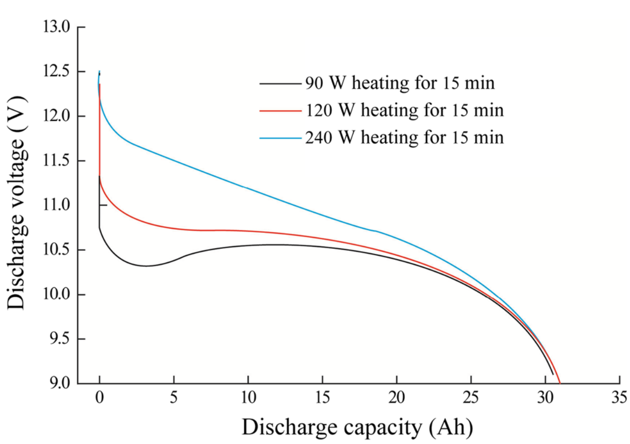

Fig. 11 35 A discharge curves of the battery packat −40 °C with heating

Figure 12 compares three 1C discharge curves of the battery pack at −40 °C after it is heated for 15 min, and three 1C discharge curves of an unheated cell at 0 °C, −10 °C, and −20 °C. The battery pack is composed of three cells, and the discharge voltage of each cell is different, thus the average discharge voltage of the three cells is used for comparison with the discharge voltage of the single unheated cell. After the battery pack at −40 °C is heated for 15 min with 90 W power, its average discharge voltage is close to the discharge voltage of the unheated cell at −20 °C at the beginning of the discharge, and higher than the discharge voltage of the unheated cell at −20 °C at the middle and late stages of the discharge. The discharge capacity of the battery pack at −40 °C heated for 15 min with 90 W power is almost equal to the discharge capacity of the unheated cell at −10 °C. These results suggest that part of the heat generated by the process of battery pack discharging has the effect of heating the battery pack after the external heating stops.

After the battery pack at −40 °C is heated for 15 min with 120 W power, its average discharge voltage is slightly below the discharge voltage of the unheated cell at −10 °C at the beginning of the discharge, and almost equal to the discharge voltage of the unheated cell at −10 °C at the middle and late stages of the discharge. After the battery pack at −40 °C is heated for 15 min with 240 W power, its average discharge voltage is slightly above the discharge voltage of the unheated cell at 0 °C at the beginning of the discharge, and slightly below the discharge voltage of the unheated cell at −0 °C at the middle and late stages of the discharge.

7.2 Charge performance of battery pack after 15 min of heating at −40 °C

Figure 13 compares five 1C constant current charge curves, including one charge curve of the battery pack after

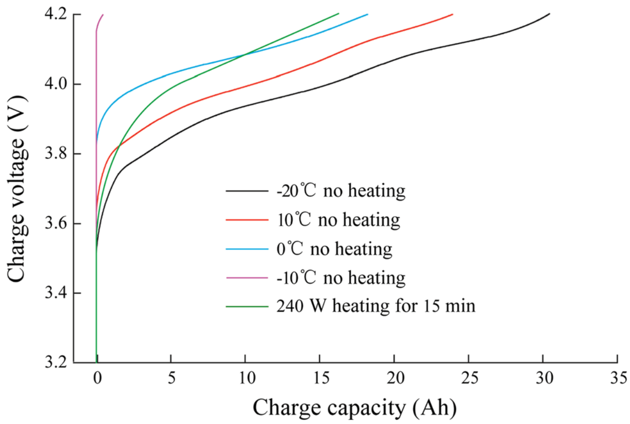

Fig. 13 35 A charge curves of the unheated cell and heated battery pack

it is heated for 15 min and four charge curves of an unheated cell at 10 °C, 0 °C, −10 °C, and −20 °C. The charge performance of the battery pack heated is improved significantly by heating. After the battery pack at −40 °C is heated for 15 min with 240 W power, its charging performance is close to the charging performance of the unheated cell at 0 °C. The main consideration for low-temperature charging performance is the heating time and heating uniformity, which can be controlled when the battery pack is heated by an external power supply.

7.3 Pulse charge-discharge performance of battery pack at −40 °C after 15 min of heating

The result experiments reported above demonstrate that the low-temperature charge-discharge performance of the battery pack heated in low temperature is improved significantly, and can be draw by the above experiments on the low-temperature heating. The full energy storage capacity can be achieved. However, the maximum charge-discharge power of the heated battery pack heated at −40 °C cannot be achieved because the heated battery pack is always charged or discharged at 1C constant current. Poor voltage performance evident in Figs. 6 and 8 prevents the use higher constant currents. Therefore, some experiments were performed using pulse charge-discharge of the heated battery pack at low temperature. Firstly, the battery pack was charged at 1C/3 at room temperature. Secondly, the battery pack was placed at −40 °C for eight hours to reach thermal equilibrium. Thirdly, the battery pack was heated for 15 min with 90 W power, and finally the battery pack was subjected to charge and discharge pulse currents. The pulses had the minimum discharge current of 17.5 A and maximum discharge current of 280 A and minimum charge current of 17.5 A and maximum charge current of 210 A. This pulse profile was designed to discharge the battery pack as quickly as possible.

The charge-discharge curve is shown in Fig. 14 together with the pulse current. In order to show the charge-discharge curve more clearly, the pulse curves at 90% state of

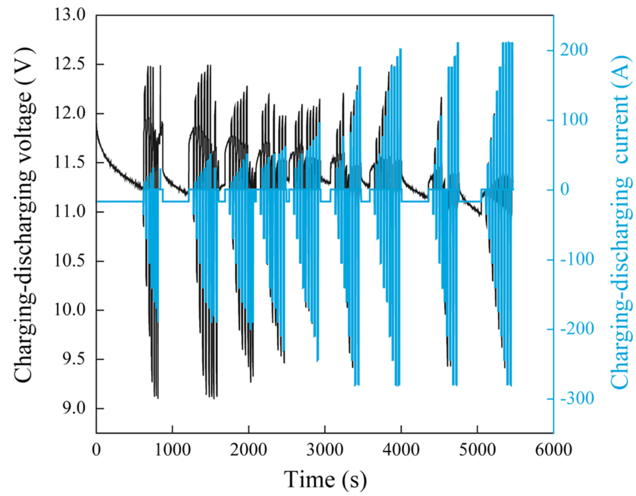

Fig. 14 Charge-discharge pulse curve of battery pack heated at −40 °C

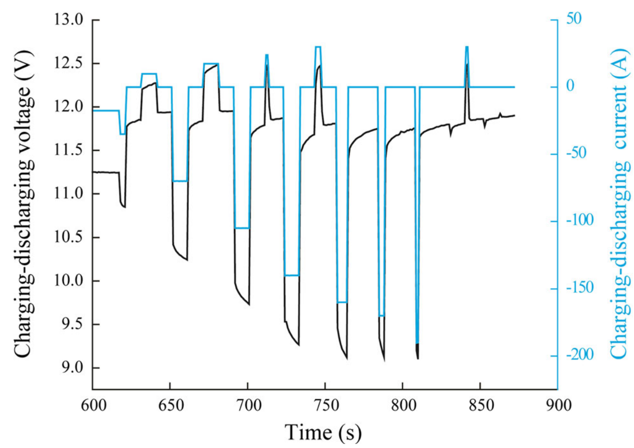

Fig. 15 Charge-discharge pulse curve at SOC 90%

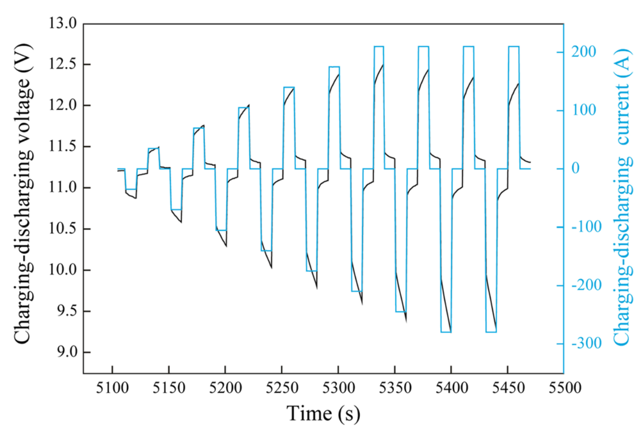

Fig. 16 Charge-discharge pulse curve at SOC 10%

charge (SOC) and 10% SOC are shown in Figs. 15 and 16. At 90% SOC, in Fig. 15, the maximum discharge current of the heated battery pack is near 210 A (6C). At the 10% SOC, in Fig. 16, the maximum discharge current of the heated battery pack is near 280 A (8C). The unheated battery pack at −40 °C cannot be charged and discharged at such high currents. Therefore, the heating method can effectively improve the discharge performance of the battery pack at low temperatures.

8 Conclusion

This paper reports a series of experiments on the low-temperature charge-discharge of a 35Ah@3.7V $LiMn_2O_4$ battery cell and a battery pack comprising three cells. The results show that the charge-discharge performance of the cell reduces significantly with the decrease of temperature, and the useable capacity of the cell becomes negligible at −20 °C. Therefore, the cell should be heated to improve its low-temperature performance.

A wide-line metal film heating mechanism was introduced to the battery back and improved its low-temperature performance significantly. After heating for 15 min at powers between 90 W and 240 W, the voltage and power performance of the battery pack were improved at 1C charging and discharging rates, and the discharging capacity of the battery pack was restored almost to its room-temperature level, while its charging capacity was restored to approximately half its room-temperature level.

Pulse charge-discharge experiments were performed on the battery pack at −40 °C after heating for 15 min. High pulse discharge currents were achieved, between 6C and 8C rates, giving an average discharge rate of 4.5C and a discharge capacity of 80% of the room-temperature discharge capacity. Charging with pulse currents is ongoing research. The battery pack at −40 °C only needs to be preheated at the beginning, because its temperature can be maintained thereafter by the heat that is produced during the charging and discharging process.

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